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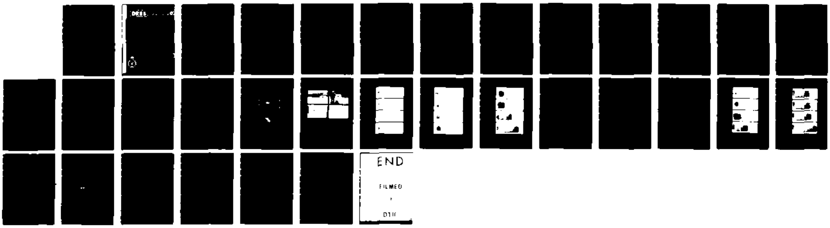

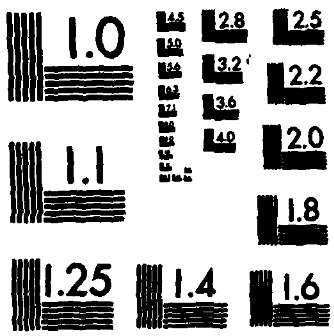

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DIRECT INITIATION OF DETONATION IN UNCONFINED ETHYLENE-AIR MIXTURES — INFLUENCE OF BAG SIZE (U)

by

S.B. Murray*, I.O. Moen*, J.J. Gottlieb**, J.H. Lee***,
C. Coffey* and D. Remboutsikas***

Project No. 27C10

December 1982

* Defence Research Establishment Suffield
** University of Toronto Institute for Aerospace Studies
*** Department of Mechanical Engineering, McGill University, Montreal, Canada

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+ Presented at the Seventh International Symposium on Military Applications of Blast Simulation, Medicine Hat, Alberta, 13 — 17 July 1981.

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ABSTRACT

The results of a series of field tests performed to determine the critical energy required for initiation of detonation in ethylene-air mixtures are described and discussed, with particular emphasis on the influence of the bag size on the initiation and propagation of detonation. The tests were performed in a plastic bag 10 m long with a cross-sectional area of 1.83 m $\times$ 1.83 m using discs of Detasheet explosive as initiator charges at one end of the bag.

(U)

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The valuable assistance of J. Funk and D. Ritzel during the test period and in the preparation for the tests is gratefully acknowledged. We would also like to thank R. Knystautas for advice on experimentation, B. Luna for assistance with recording, C. Sutherland for assistance with firing, C. McIvor for high-speed cinematographic photography, and J. McAndless and C. Chenier for calibrating the infrared gas analyzer. The field support of R. Withers, D. Hogg and others is gratefully acknowledged, as is the illustration effort by S. Kelly.

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1. INTRODUCTION

The use of fuel-air explosives (FAE) in military applications such as FAE weapons and nuclear blast simulation requires a basic understanding of the detonability properties of FAE. Remote from physical boundaries and other perturbations, the propagation of detonations in uniform FAE clouds can be adequately described by parameters such as detonation velocity and pressure. These parameters can be obtained from standard Chapman-Jouguet (C-J) calculations. However, from the practical point of view, one is also interested in the critical conditions for onset of detonation in a given FAE, the influence of non-uniform fuel concentration and boundaries on the propagation of detonations, and the transmission of detonation, either from one cloud to another or through openings such as ventilation shafts of military or civilian installations. In order to address these questions, a more fundamental understanding of the detonability properties of FAE is required.

One of the basic properties which characterize FAE is the critical initiation energy. The critical energy (E_c) or the minimum mass (W_c) of solid explosive required for direct initiation of detonation in an unconfined FAE cloud is of both practical and fundamental significance in assessing the detonability properties of FAE. In fact, Matsui and Lee (1) have proposed that the critical energy be used to assess the relative detonation hazard of various FAE in the context of accidental explosions. The critical energy is also directly related to the minimum or critical tube diameter (d_c) for a confined detonation in a tube to transmit to an unconfined detonation. On the fundamental level, these properties are related to the coupling between chemical energy release and gasdynamics responsible for the three-dimensional transverse wave structure of detonation waves.

Theoretical models and correlations linking the detonability properties of FAE (i.e., critical energy, critical tube diameter, characteristic transverse wave structure and chemical kinetics) have been proposed (2-4). However, at the present time, there is no theory capable of predicting the critical initiation energy from system properties. The critical energy must therefore be determined experimentally. Although some critical energy data for various fuel-air mixtures are available (5,6), much of these data have been obtained without monitoring the influence of charge geometry or bag size. The importance of charge geometry is perhaps best illustrated by noting that Benedick (7) obtained detonation in stoichiometric methane-air with only 4 kg of distributed solid explosive charge, whereas the results of Bull *et al.* (8) indicate that a concentrated charge of 22 kg is required for this mixture. Benedick also demonstrated that, for a given mixture, there is a critical bag size (or cloud thickness) below which detonation will not propagate. The influence of boundary conditions on the propagation of detonations has recently been further clarified by Moen *et al.* (9). They propose that boundary conditions play an important role if the minimum dimension of the bag or explosion apparatus is less than the critical tube diameter, d_c. Thus, in order to obtain a measure of the critical energy for direct initiation in an unconfined FAE cloud, the minimum dimension of the test bag must be greater than this critical tube diameter. Furthermore, the bag must be large enough so that the influence of the initiation source can be neglected and a steady-state detonation wave established by the end of the bag.

This paper reports on the results of a series of field tests performed at the Canadian Defence Research Establishment Suffield to determine the critical energy for the initiation of detonation in lean ethylene-air mixtures. Ethylene-air was chosen on both practical and scientific considerations. Ethylene-air mixtures are relatively sensitive so that the physical dimensions (i.e., bag size) could be kept reasonably small. Furthermore, the fact that ethylene is a gas at normal atmospheric conditions permits easy handling and monitoring of gas composition. Detonations in ethylene-air mixtures

have also been extensively investigated in the laboratory. The laboratory investigation of near limit phenomena in different diameter tubes (9), and the determination of critical tube diameter for the C_2H_4-O_2-N_2 system, both in the laboratory (10) and in recent field tests (11), provide key input which can be integrated with the critical energy determination to test and refine theoretical models and correlations.

The present series of tests was designed to obtain reliable critical energy data and also to investigate the influence of bag size and charge geometry on the initiation and propagation of detonations. The experimental test facilities and diagnostics are described in detail in the next section, and the results are presented and discussed in Section 3. Concluding remarks and suggestions for further investigations are included in Section 4.

2. EXPERIMENTAL DETAILS

The tests were performed in plastic bags 10 m long with a cross-sectional area of 1.83 m × 1.83 m, constructed by wrapping 0.089 mm thick polyethylene sheet around a rectilinear lattice frame assembled from extruded aluminum tubing and cast aluminum corner pieces. The frame was supported on buried concrete blocks in such a manner that one side of the bag was always in contact with a graded gravel surface. The ignition end of the bag was covered by a square sheet of 7 mm thick plywood having a central circular hole in which the initiator charge was mounted. The other end of the bag was sealed by drawing the polyethylene material into a neck aroung the gas filling line and securing it with nylon cord. Schematic diagrams of the test facility and bag construction are shown in Figs. 1 and 2, with selected photographs of the facility included in Fig. 3.

The initiator charges used in the present test series consisted of circular discs of explosive with a nominal areal density 1.58 kg/m^2 (1.07 mm thick Dupont Detasheet). Initiation of the Detasheet was achieved by an electric detonator mounted near the center of the disc. The initiator energy was varied by using initiator discs of different diameters. In the present tests, discs with diameters ranging from 76 mm to 902 mm were employed. The total initiator energy was characterized by the total charge mass, W. The equivalent mass of tetryl is approximately 0.98 W (6). Prior to the FAE tests, the initiation system was evaluated and the air-blast characteristics from various diameter initiator charges were obtained by measuring the blast overpressure in air at different distances from the charges. These tests are described in detail elsewhere (12). See Fig. 10.

Three types of instrumentation were used to record the "details of" or "information about" initiation and propagation of detonation waves in the bag. A high-speed camera (Hycam model K20S4E) with framing rates between 1000 and 7000 frames

per second was used to obtain a photographic record of each event on 16 mm colour film (ASA 400). The time of arrival of the wave at various positions in the center of the bag was monitored by nine ionization-gap probes mounted on a rod down the center of the bag. The signals from these probes were recorded on magnetic tape using an analog recorder (Ampex FR1300). The positions of the ionization probes are shown in Fig. 2. Also shown in this figure are the positions of eight pressure transducers (PCB Piezotronics 113A24) mounted on the lattice frame. Pressure signals from six transducers were recorded on magnetic tape using a 7 channel analog recorder (Racal Thermionic Store 7D). Signals from the other two were displayed on an oscilloscope (Tektronix 7623A). Proper timing of events was accomplished by having the camera activate the firing circuit for the detonator and by also recording the time of ignition (det zero) on magnetic tape as a reference.

The desired gas mixture was prepared by continuous flow of regulated quantities of ethylene (CP grade, 99.5% pure) and bottled dry air through a specially designed mixing chamber. Flow rates were controlled by dual-stage industrial regulators and monitored by standard ball-type rotameters. The mixture was distributed throughout the bag by means of a perforated plastic tube aligned down the center of the bag. The composition of the flowing mixture and the mixture at three positions in the bag was sampled and examined at regular intervals using an infrared gas analyzer (Wilks Miran 80).

Typically, gas filling was carried out in two stages. In the first stage, a mixture having twice the fuel concentration ultimately desired was flowed at the maximum possible rate of 250 liters per minute for approximately 20 minutes. Subsequently, in stage two, the outgoing mixture composition was adjusted to that required globally in the bag. Since fine tuning of the composition was by trial and error, fill times were variable, ranging from 70 to 180 minutes. The average fill time was 97 minutes. Uniformity of mixture composition in the bag prior to ignition was within ± 0.1% C_2H_4 as verified by infrared analysis of samples from the three sampling ports in the bag. One gas sampling port was located at each end of the bag with a third port in the middle. The sampling ports at the ends were positioned along the central axis of the bag, whereas the middle sampling port was situated on the bag periphery.

3. RESULTS AND DISCUSSION

Selected frames from the high-speed cinematographic records, showing both failure to initiate detonation and successful initiation in an ethylene-air mixture with 6.4% C_2H_4, are included in Fig. 4. Failure of the hemispherical blast wave from a

Detasheet charge of mass 9×10^{-3} kg (disc diameter of 76 mm) to initiate detonation is clearly seen in Fig. 4a. Successful initiation achieved with a Detasheet charge of mass 18×10^{-3} kg (disc diameter of 102 mm) is seen in Fig. 4b. The first few frames of this latter sequence show the initiation of a detonation which grows in a spherical manner until the bag boundaries are reached. The subsequent propagation of a slightly curved detonation wave extending across the whole cross-sectional area of the bag can be seen in the later frames. This detonation wave propagates at a constant velocity of about 1820 m/s. Similar detonation initiation and subsequent propagation of detonation with constant velocity within 3% of the theoretical C-J velocity (V_{CJ}) were observed in all ehtylene-air mixtures near stoichiometric composition (6.54% C_2H_4). At a composition of 3.9% C_2H_4, however, strong periodic oscillations in velocity were observed, with a mean velocity $\sim$10% lower than the theoretical C-J value, indicating that the bag boundaries may have been influencing the propagation of the detonation wave.

The detonation velocities observed for different ethylene-air compositions are compared with the corresponding theoretical C-J values in Fig. 5. Also included in this figure are the detonation velocities observed in different diameter tubes (9). Notice that detonations having velocities less than the theoretical C-J values are observed both in the large diameter tube ($d = 145$ mm) and in the bag for lean ethylene-air compositions. In the tube, detonations at these compositions are characterized by a low-mode transverse wave structure which is stabilized by the tube walls. In an unconfined situation there is no mechanism for external stabilization of transverse waves, and detonations in FAE whose characteristic critical tube diameter, d_c, is greater than the minimum dimension of the cloud are expected to fail under the influence of the rarefaction waves penetrating from the sides of the cloud (9).

Critical tube diameter data for ethylene-air are available from the large-scale field tests at Raufoss, Norway (11). These data, together with the predictions of a theoretical correlation proposed by Moen *et al.* (9) are shown in Fig. 6. Also shown in this figure are the predicted critical tube diameters, d_c, based on the observation by Mitrofanov and Soloukhin (13) and the criterion proposed by Edwards *et al.* (14) that $d_c = 13S$, where S is the characteristic transverse wave spacing obtained either by direct measurement (15) or by monitoring the onset of single-head spin in tubes (9,16). For stoichiometric C_2H_4-air (6.54% C_2H_4) the critical tube diameter or minimum dimension of an unconfined detonable cloud is approximately 0.36 m. This is predicted to increase to 7 m at 3% C_2H_4. With the minimum dimension of the bag in the present experiments (1.83 m) the boundaries are expected to begin to influence the propagation between 4% and 3.8% C_2H_4. This is exactly the range of composition in which a detonation with strong periodic oscillations in velocity was observed.

The propagation velocities observed at various positions in the bag for detonations in ethylene-air mixtures with 6.4% C_2H_4 and 3.9% C_2H_4 are compared in Fig. 7. At 6.4% C_2H_4 the detonation is observed to propagate at an approximately steady velocity close to V_{CJ}, whereas at 3.9% C_2H_4 the detonation propagates in an unsteady manner with large excursions in velocity. The period of oscillation is about 2.5 m. The mechanism responsible for this unsteady behavior is not understood, but the observations of these strong oscillations near critical conditions where the critical tube diameter is approximately equal to the minimum bag dimension suggests that the thin plastic walls could be instrumental in maintaining the wave propagation. Unfortunately, the bag is not long enough to determine whether the detonation continues to propagate in this unsteady manner, decays to a decoupled flame-shock wave complex, or transits to a C-J detonation.

Similar unsteady propagation was also observed by Benedick (7) in his methane-air experiments in a 2.4 m × 2.4 m × 12 m bag. The critical tube diameter for methane-air is predicted to be considerably larger than 2.4 m (15), so that the bag boundaries may also be influencing the propagation in his experiments. In confined situations, such as tubes, unsteady propagation in the form of galloping detonations has been reported by many authors (17-19). Recent investigations of near limit phenomena in tubes have shown that this latter type of unsteady propagation can be triggered as a result of coupling between combustion zone instabilities and the acoustic modes of the tube (9).

Further research is clearly required in order to clarify the role of partially-confining boundaries, such as those of the plastic bag used in the present tests. Although this problem was not addressed directly, the influence of the thin plastic (used in the construction of the bag) on the propagation of detonations was investigated by placing a sheet of this material in the bag 5.16 m from the ignition end. Except for a 0.25 m diameter central hole, the plastic sheet covered the entire cross section of the bag. The size of the hole was chosen to be smaller than the critical tube diameter, $d_c = 0.32$ m, characteristic of the ethylene-air mixture used (7.2% C_2H_4), so that the detonation would not have been transmitted through an identical orifice hole in a solid obstruction (20). Selected frames from the high-speed cinematographic record of this test are shown in Fig. 8. The corresponding velocity profile is shown in Figure 9. A marked influence of the thin plastic obstruction on the propagation is observed in both of these figures. In fact, the transmission through the central hole is similar to that observed in detonation transmission from a tube (11,13) or a channel (14,20) into an unconfined region, except that in the present case the hole diameter is less than the critical tube diameter so that re-initiation must be aided by the wave which breaks through the plastic

sheet (see Fig. 8). If a thin plastic obstruction can interfere with the propagation of the detonation in the above manner, then the plastic bag boundaries can certainly influence the propagation. According to our previous discussion, this influence becomes important when the minimum dimension of the bag is smaller than the characteristic length scale, d_C, associated with the FAE mixture.

One of the aims of the present investigation was to determine the critical energy, E_C, or the charge weight, W_C, required to initiate detonation in lean ethylene-air mixtures. In the near field the initiating blast wave from charges in the form of Detasheet discs will not be spherical. In fact, the blast wave will initially be approximately planar, approaching spherical decay in the far field. The air-blast characteristics of the initiator charges were obtained in an investigation undertaken prior to FAE tests. In this investigation, which is reported elsewhere (12), the blast-wave decay along the central axis perpendicular to the plane of the charge was determined by measuring the blast-wave overpressure at different distances from the charge as illustrated in Fig. 10. Reduced overpressure-distance data are shown in Fig. 11. In order to compare with the decay of a spherical blast wave from a concentrated TNT charge (21), the distance from the charges, R in meters, is normalized by the cube root of the charge mass, W in kilograms. Although the results show approximate scaling with $R/W^{1/3}$, indicating spherical decay, the peak overpressure is much higher than from a concentrated TNT charge in the near field. However, the peak overpressure appears to be approaching that from an equivalent TNT charge in the far field. It is clearly important to determine the influence of this higher near-field peak overpressure on the initiation process. The results of the present investigation do not cover a wide enough range of charge geometries to be able to quantify this influence. Thus, for the purposes of comparison with other critical energy data, the initiator charge was characterized by the total mass, W, of the Detasheet disc. The equivalent mass of tetryl based on solid-explosive detonation energy is ~ 0.98 W (6), corresponding to an explosive energy release of about 4.18×10^6 Joules per kilogram of Detasheet charge.

The critical charge masses for ethylene-air compositions between 3.9% and 6.4% C_2H_4 by volume, determined by a Go-No Go procedure, are shown in Fig. 12. The results are in good agreement with results obtained in other investigations near stoichiometric composition (5,6,22). The present results also cover a wider range of compositions, thus providing a more critical test for theoretical models and correlations. A model relating the critical energy and the critical tube diameter has been proposed by Matsui and Lee (1). By equating the critical energy to the work done by the combustion products behind a C-J detonation wave emerging from a tube of diameter d_C into an unconfined region, over a period equal to the time for the expansion wave from the side to reach the center, they obtain the following relation:

$$E_C = \frac{\pi p_D u_D}{24 c_D} d_C^3 \tag{1}$$

where p_D, c_D and u_D are the C-J detonation pressure, sound speed and particle velocity, respectively. The energy in Eqn. 1 includes only the work done by the unattenuated detonation core, which represents only a fraction of the energy responsible for the re-establishment of the detonation in the spherical region. The critical initiation energy could therefore be considerably larger than that predicted by Eqn. 1. For stoichiometric ethylene-air a critical charge mass of 1.25×10^{-2} kg, as indicated by the results shown in Fig. 12, gives a critical energy 5.77 times larger than that predicted by Eqn. 1, based on the explosive energy release of 4.27×10^3 kJ/kg for tetryl. In other words, the energy obtained from Eqn. 1 represents only 17% of the total critical energy required for direct initiation in stoichiometric ethylene-air. The solid curve in Fig. 12 is obtained by assuming that this fraction is the same for all ethylene-air compositions.

4. CONCLUSION

Detailed observation of initiation and propagation of detonations in lean mixtures of C_2H_4-air in a large bag 1.83 m × 1.83 m × 10 m shows that the thin plastic bag walls may be influencing the propagation. This influence becomes important when the characteristic length scale, d_C, associated with the FAE is greater than the minimum bag dimension. For ethylene-air away from limit conditions (i.e., $d_C < 1.83$ m or equivalently $\% C_2H_4 > 3.9\%$) constant velocity C-J detonations are observed. However, near limit conditions (i.e., $d_C \cong 1.83$ m or $\% C_2H_4 \cong 3.9\%$) strong periodic oscillations in velocity are observed, with a mean velocity 10% lower than the C-J velocity, indicating that boundary conditions may be instrumental in maintaining the detonation wave. These observations are consistent with the proposal that the boundary conditions play an important role if the minimum dimension of the bag or explosion apparatus is less than d_C (9). The critical tube diameter, d_C, characteristic of a given mixture is also equivalent to the minimum dimension required for a cloud consisting of that mixture to be detonable. Further research is required in order to clarify the role of partially-confining boundaries such as those present in bag tests.

The critical energies for ethylene-air compositions between 3.9% and 6.4% C_2H_4 by volume have been determined by a Go-No Go procedure. For 6.4% C_2H_4 it is found that detonation can be initiated by a circular disc of Detasheet explosive of diameter 102 mm, corresponding to a charge mass of 18×10^{-3} kg, whereas a Detasheet disc 902 mm in diameter (1.09 kg) is not sufficient to initiate a detonation in a 3.4% C_2H_4

mixture. The critical energy or minimum charge mass results are in good agreement with previous results near stoichiometric composition and provide further data for lean ethylene-air mixtures. The variation in critical energy, E_c, with composition is described reasonably well by the work model proposed by Matsui and Lee (1), although the energy predicted by this model is only about 17% of the measured critical energy.

Further refinements in both theory and experiment are necessary in order to obtain a basic understanding of the detonability properties of FAE. The present results, together with the critical tube diameter results from the Raufoss tests (11), make the ethylene-air system ideal for further investigation and for comparison purposes.

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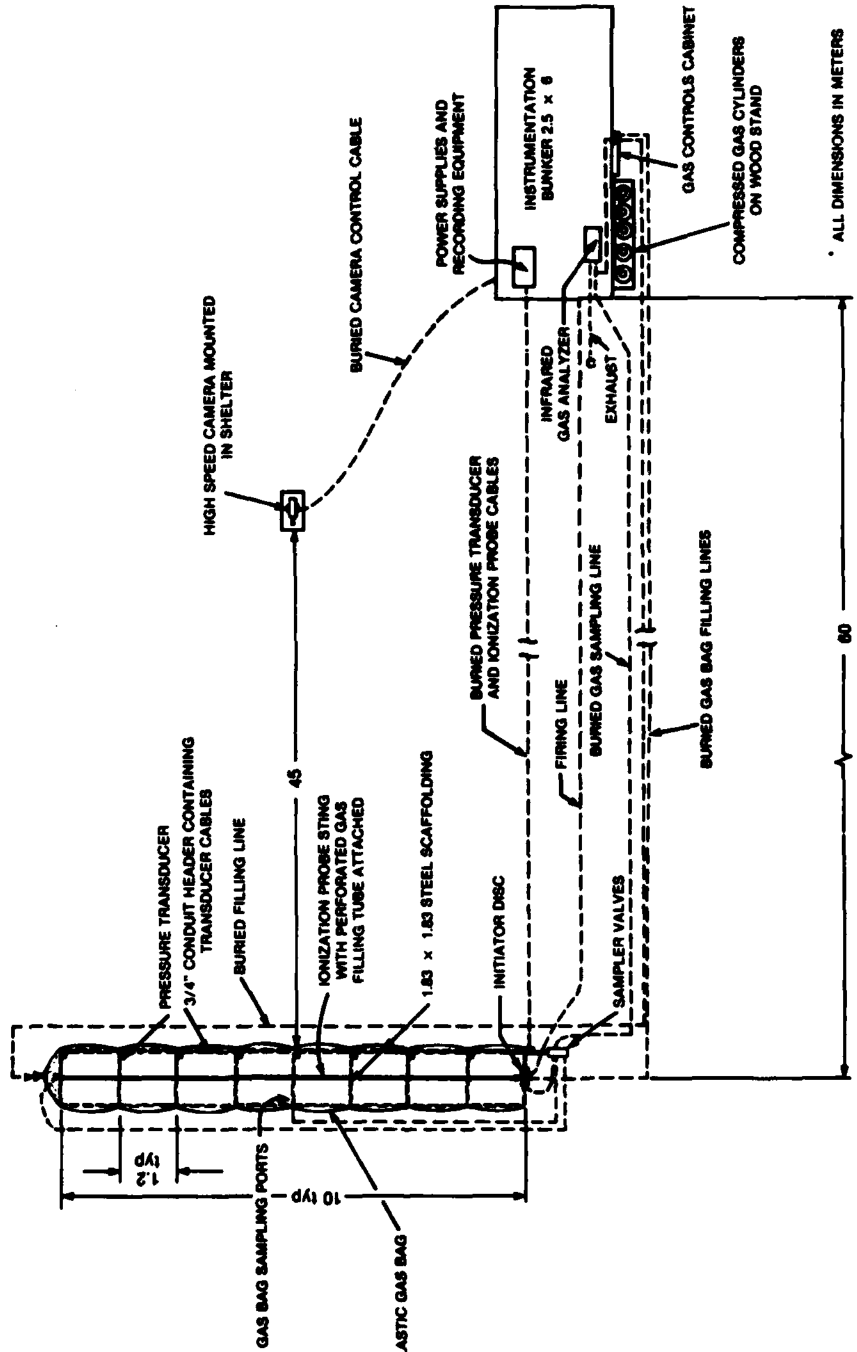

FIG. 1 — GENERAL LAYOUT OF FAE FACILITY

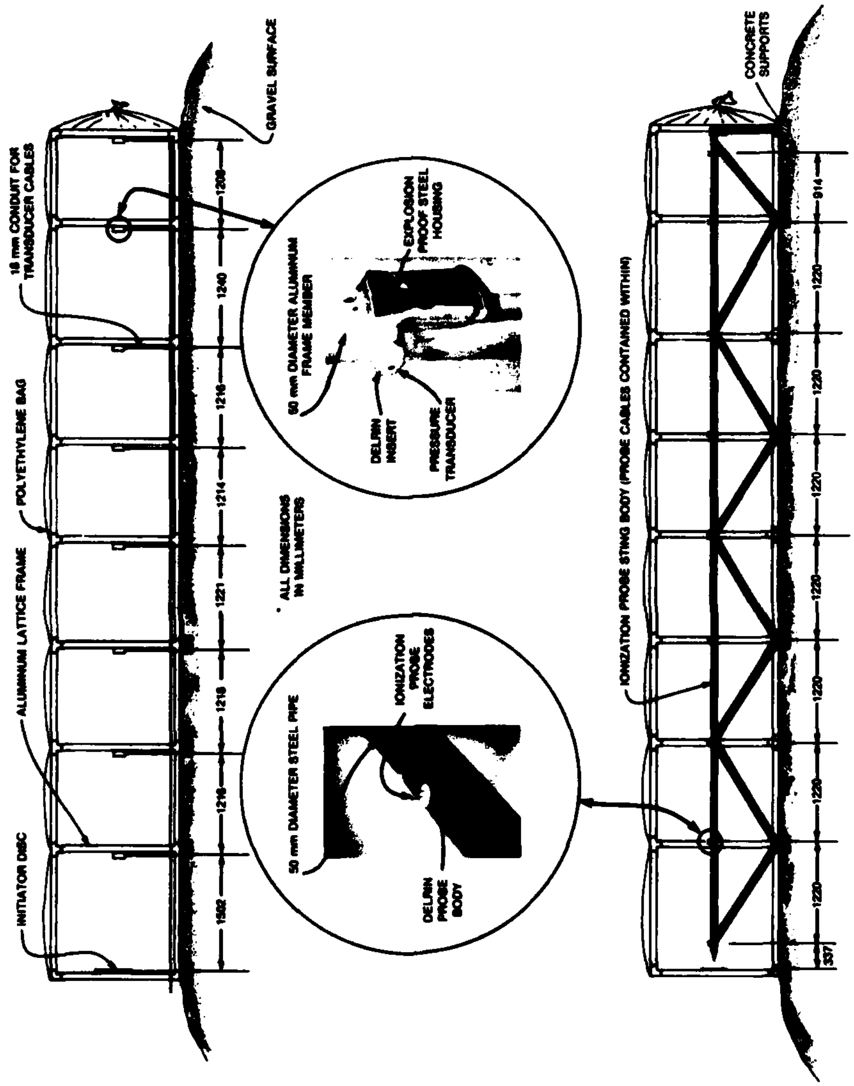

FIG. 2 — PRESSURE TRANSDUCER AND IONIZATION PROBE POSITIONS AND DETAILS

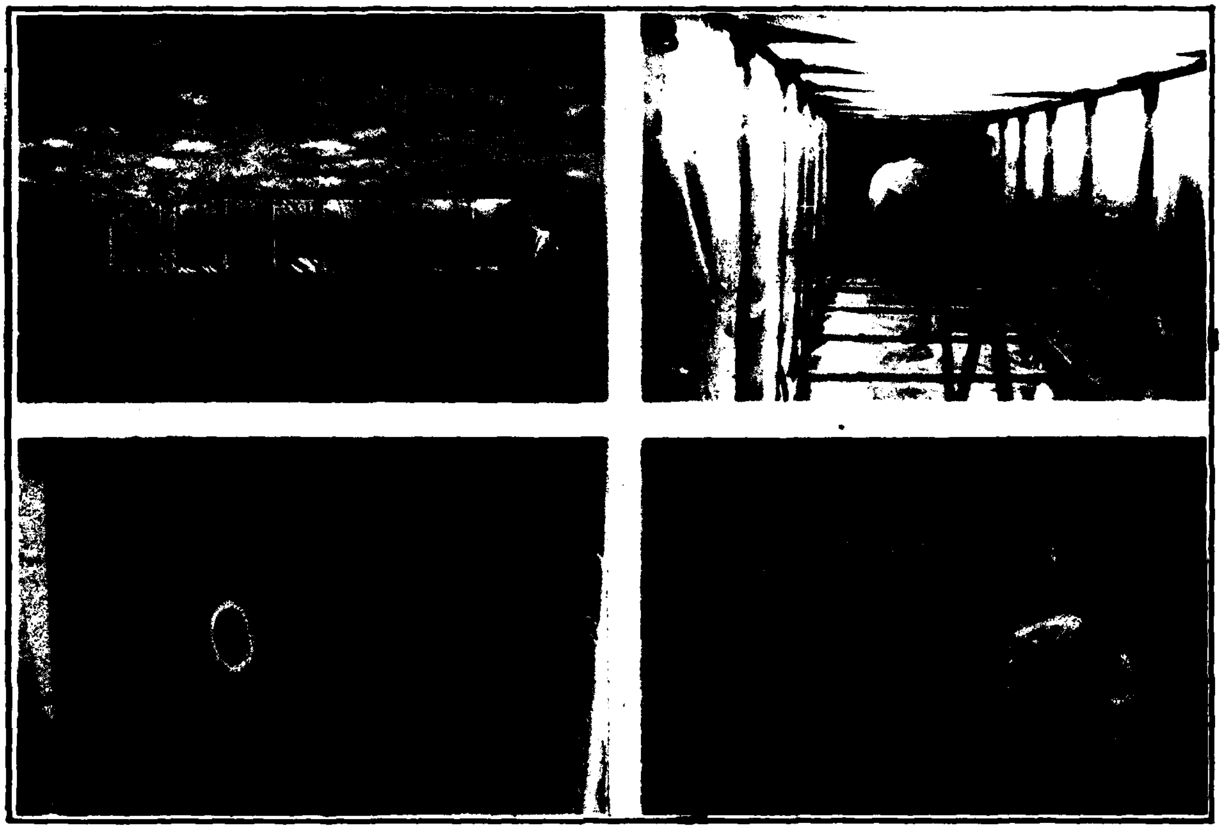

FIG. 3 — GAS BAG CONFIGURATION

A) EXTERIOR OF BAG READY FOR TESTING
B) INTERIOR OF BAG SHOWING IONIZATION PROBE STING, PRESSURE TRANSDUCERS, AND CIRCULAR HOLE CUT IN IGNITION END
C) IGNITION END OF BAG SHOWING INSTALLED INITIATOR DISC
D) FAR END OF BAG

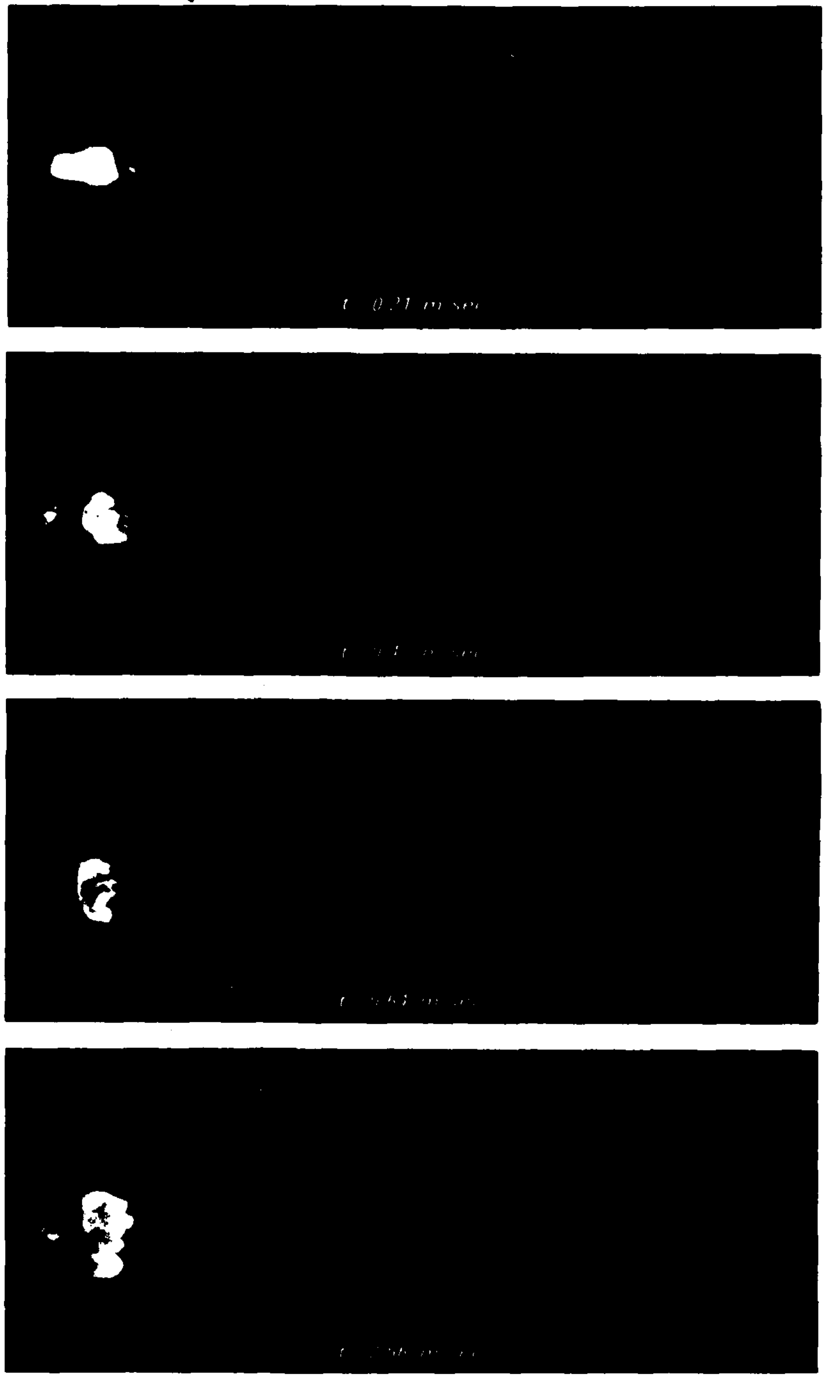

Fig. 4a. - Selected frames from cinematographic record — unsuccessful initiation of 6.4% C_2H_4 in C_2H_4-air with initiator disc of 76 mm diameter (9×10^{-3} kg).

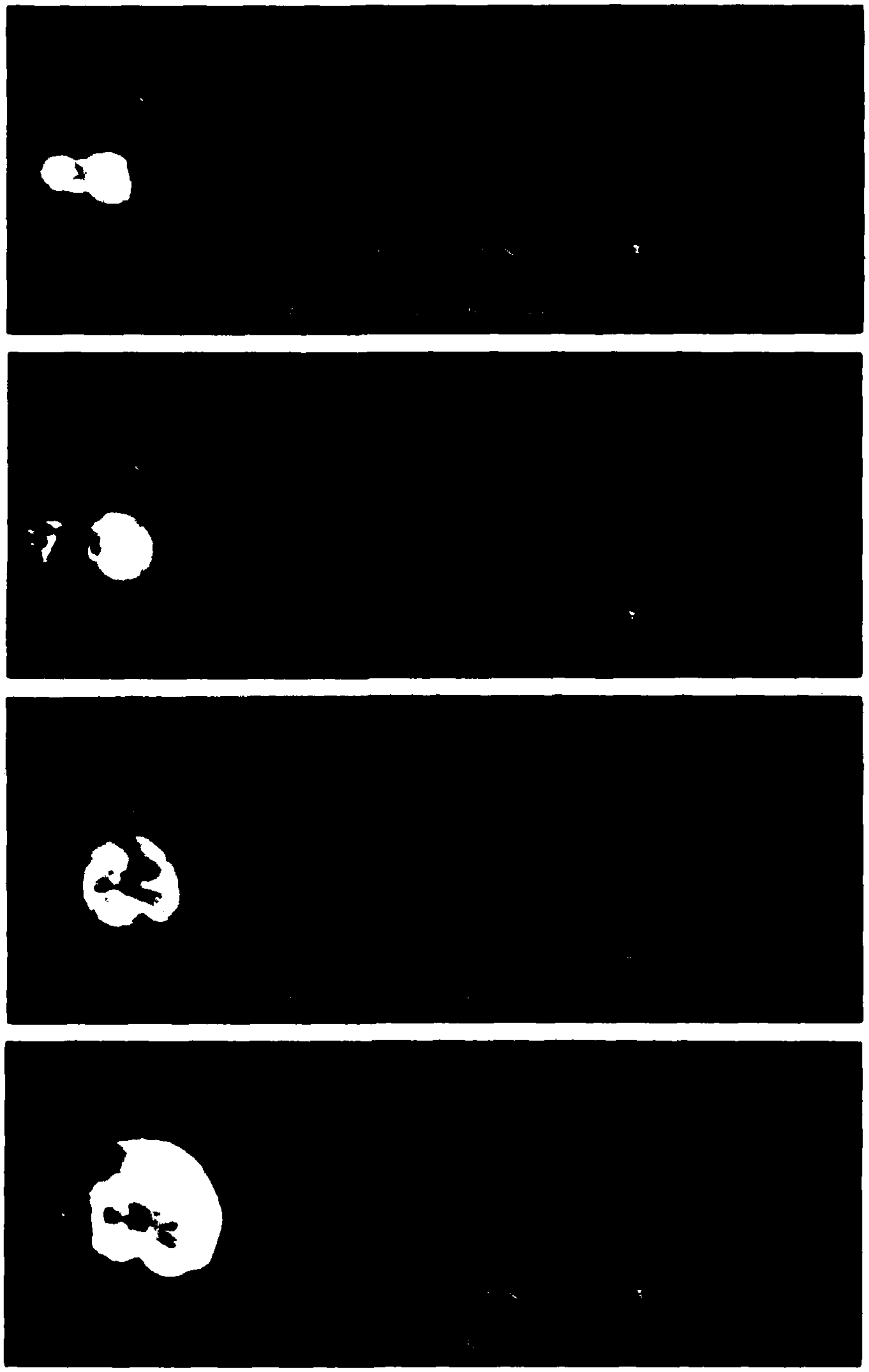

Fig. 4b. – Selected frames from cinematographic record — successful initiation of 6.4% C_2H_4 in C_2H_4-air with initiator disc of 102 mm diameter (18×10^{-3} kg).

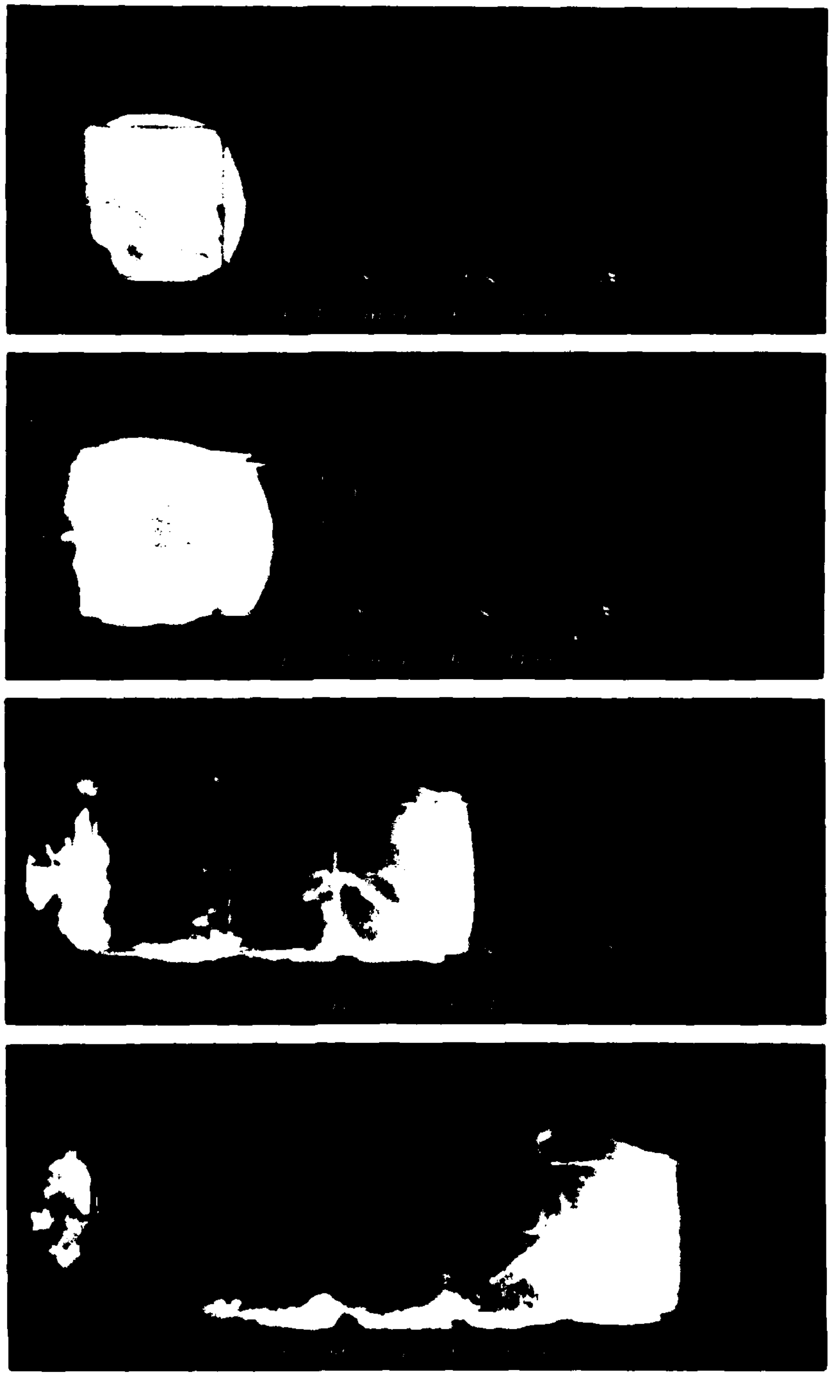

Fig. 4b. - (cont'd) Selected frames from cinematographic record — successful initiation of 6.4% C_2H_4 in C_2H_4-air with initiator disc of 102 mm diameter (18×10^{-3} kg).

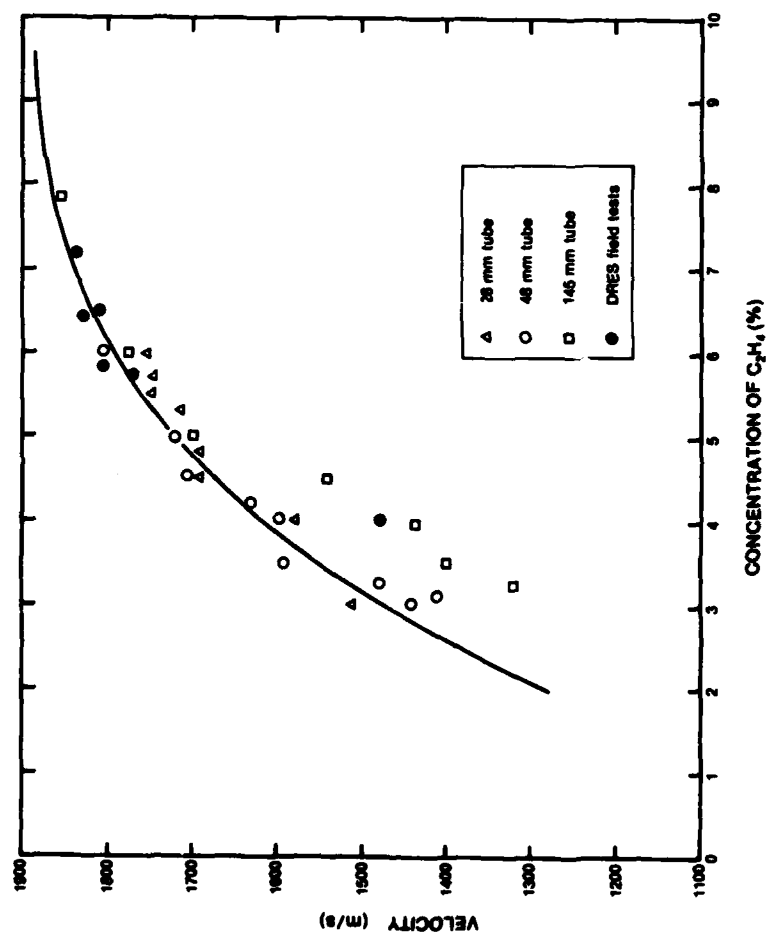

Fig. 5 – Detonation velocity vs. composition (% C_2H_4 in C_2H_4-air). The solid curve shows the theoretical C-J velocity. The tube results are from Ref. 9.

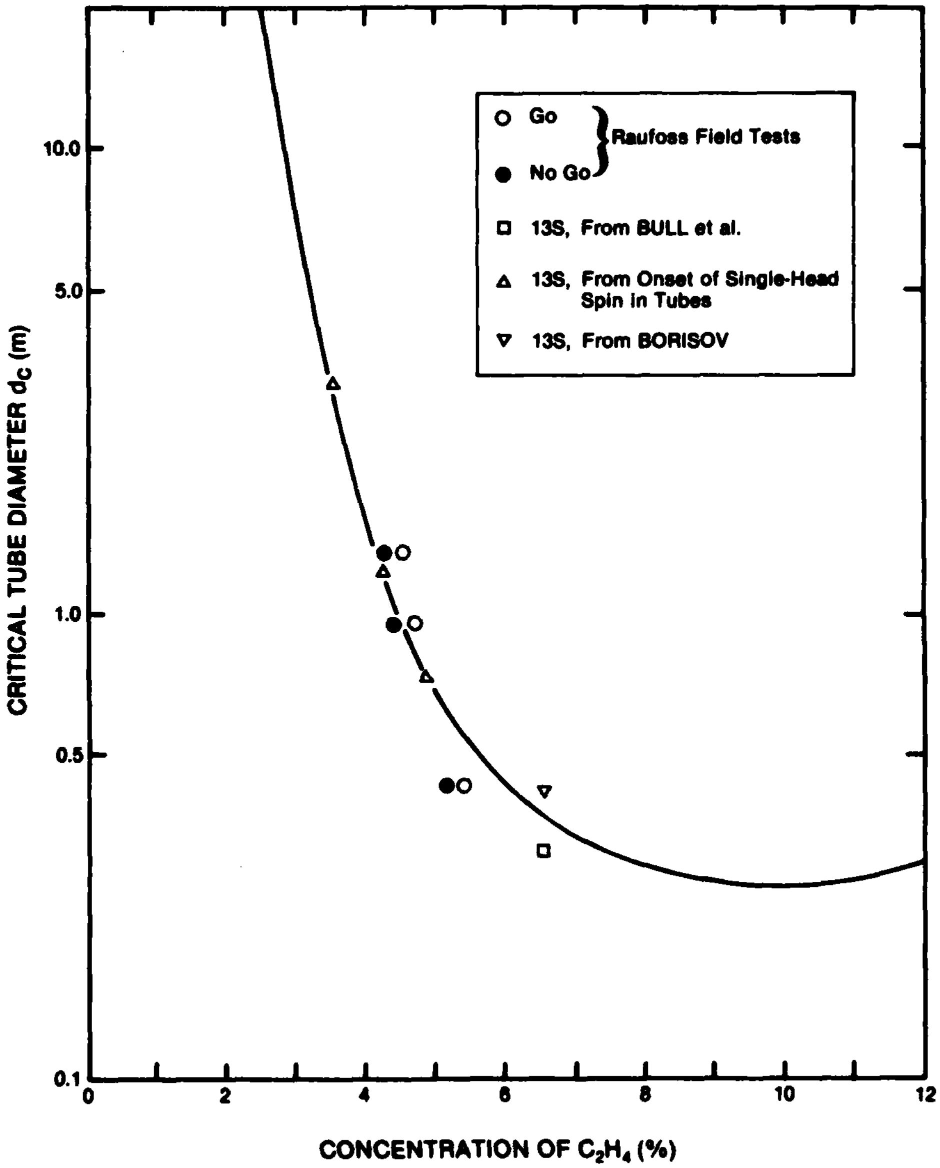

Fig. 6 - Critical tube diameter for C_2H_4-air. Raufoss Field Tests — Ref. 11; Bull et al. — Ref. 15; Onset of Single-Head Spin — Ref. 9; Borisov — Ref. 16.

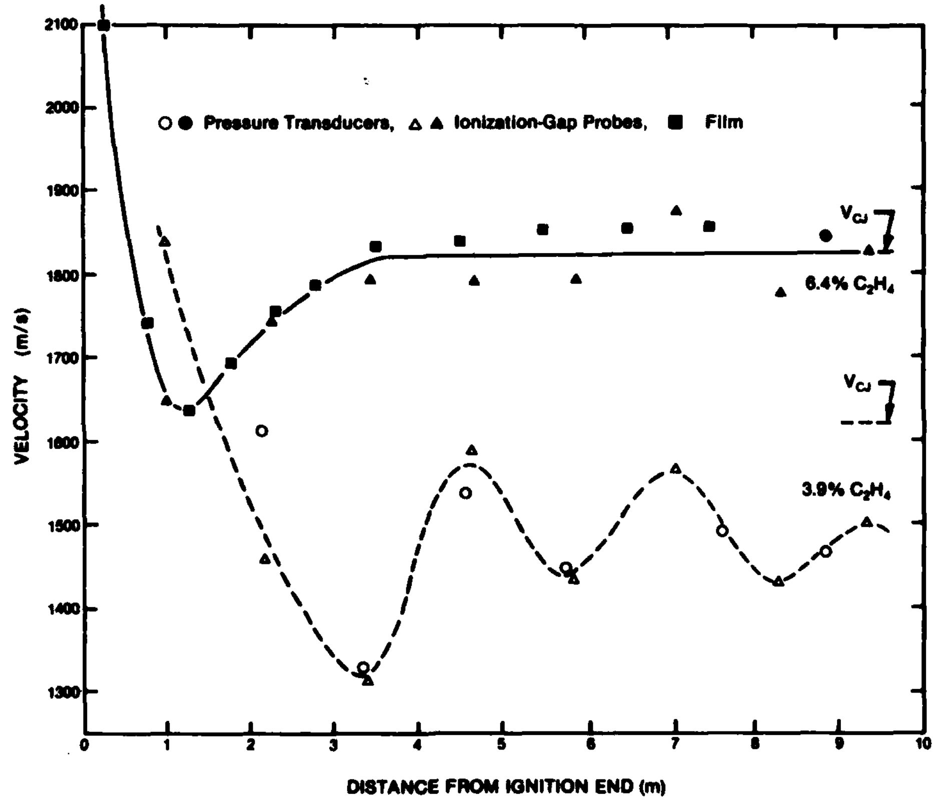

Fig. 7 - Detonation velocity observed at various positions along the bag showing steady propagation for 6.4% C_2H_4 in C_2H_4-air and unsteady propagation for 3.9% C_2H_4 in C_2H_4-air.

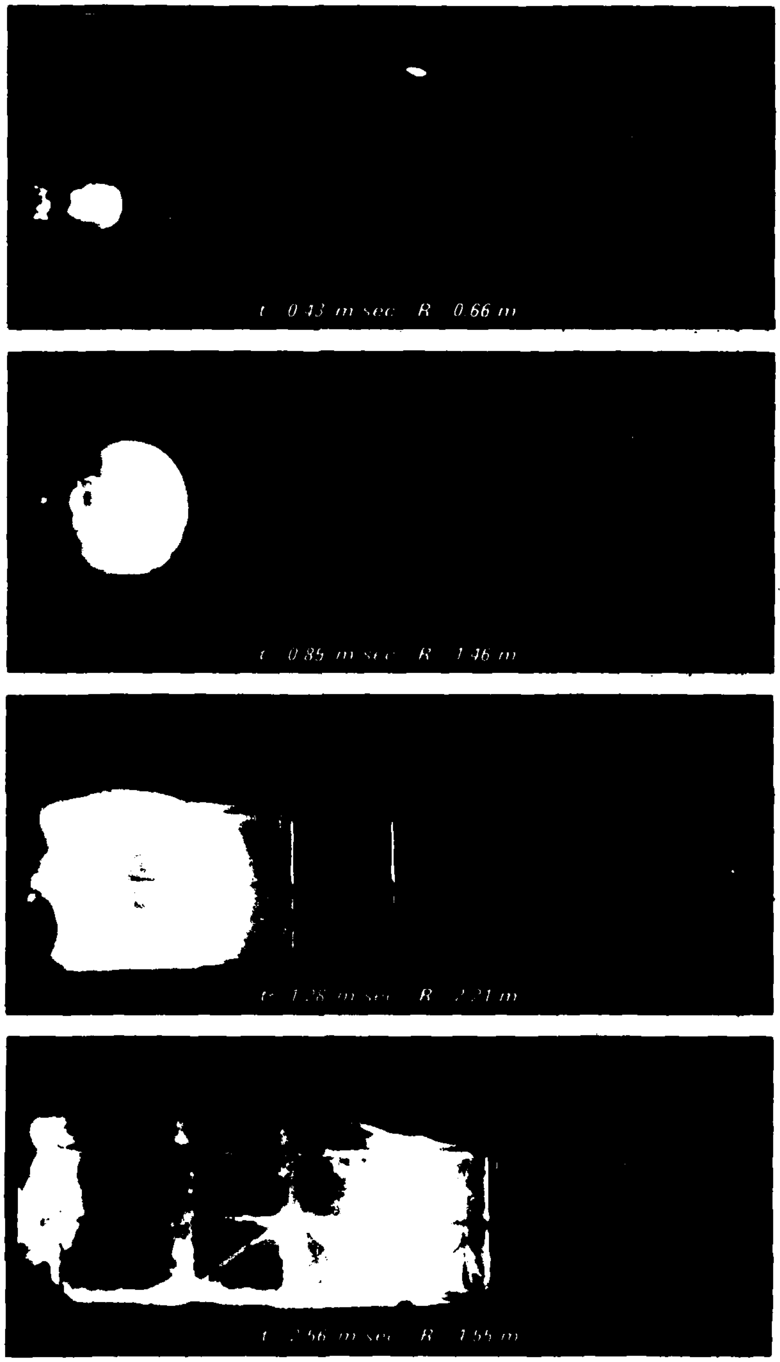

Fig. 8 - Selected frames from cinematographic record — propagation of detonation in 7.2% C_2H_4 in C_2H_4-air, showing initiation in early frames and successful transmission through a hole in a plastic sheet in later frames.

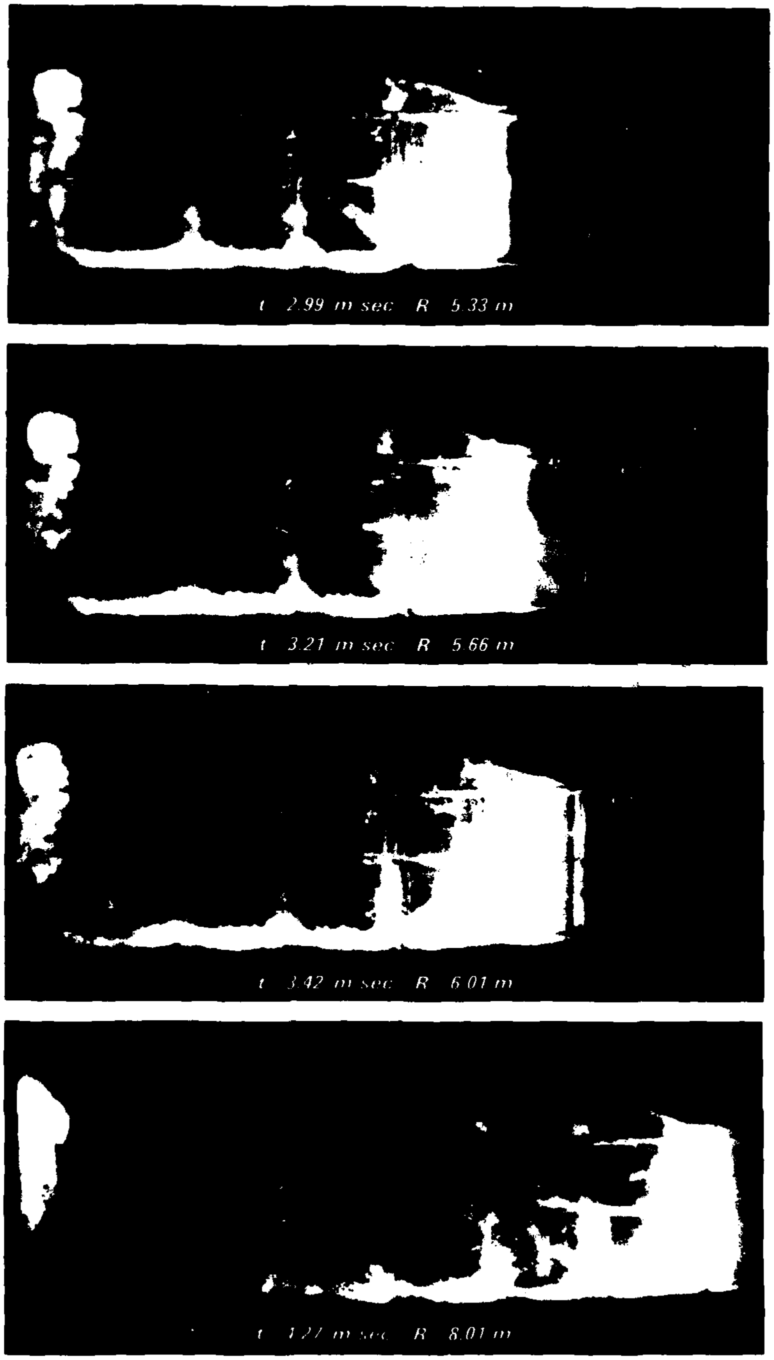

Fig. 8 – (cont'd) Selected frames from cinematographic record — propagation of detonation in 7.2% C_2H_4 in C_2H_4-air, showing initiation in early frames and successful transmission through a hole in a plastic sheet in later frames.

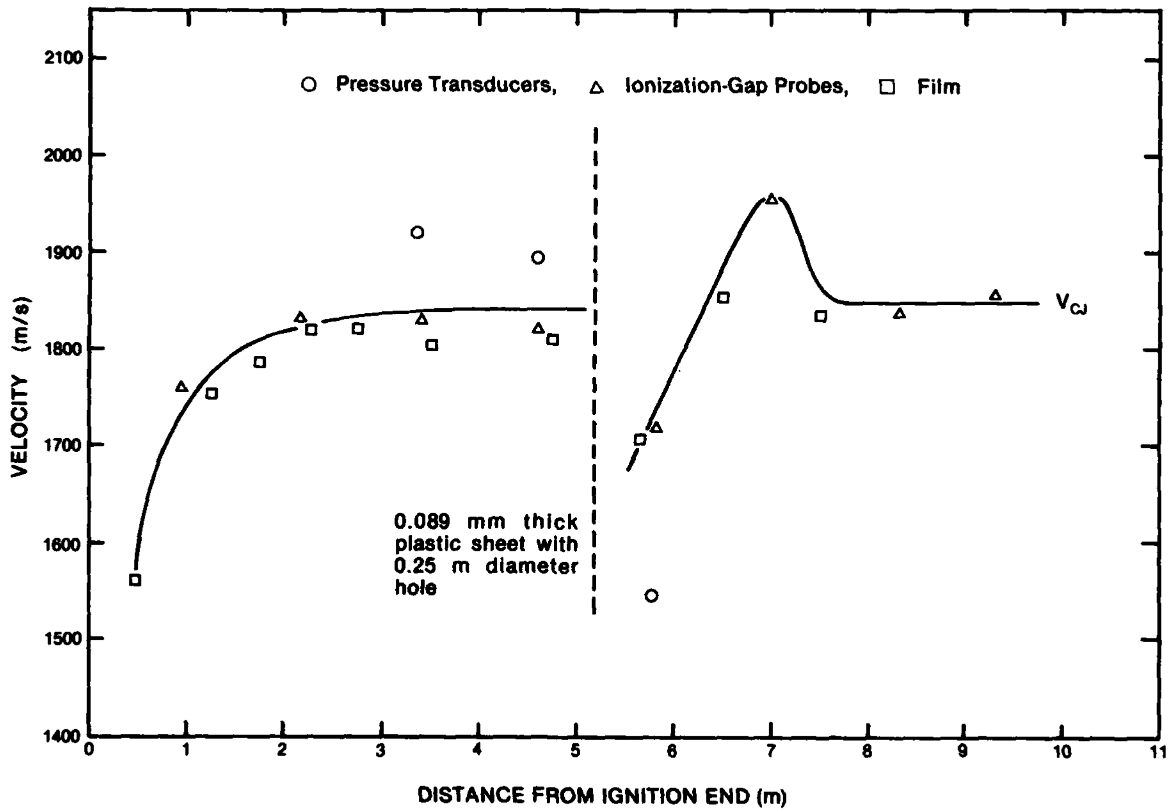

Fig. 9 – Velocity profile for the case of transmission of detonation through a 0.25 m diameter hole in a plastic sheet located 5.16 m from the ignition end of the bag. The gas mixture is 7.2% C_2H_4 in C_2H_4-air.

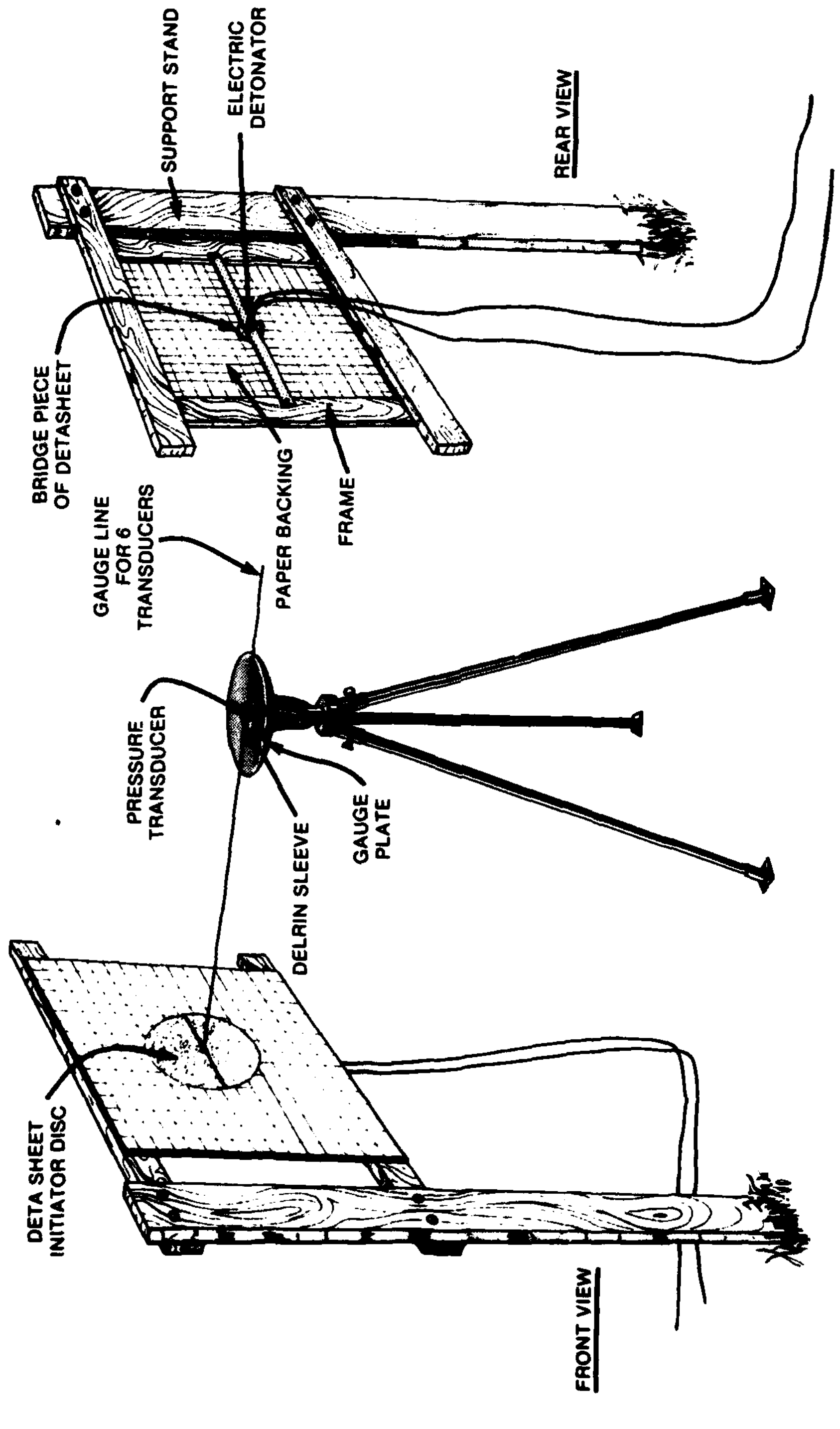

FIG. 10 — ILLUSTRATION OF APPARATUS USED FOR TESTING DETASHEET (PETN) INITIATOR DISCS

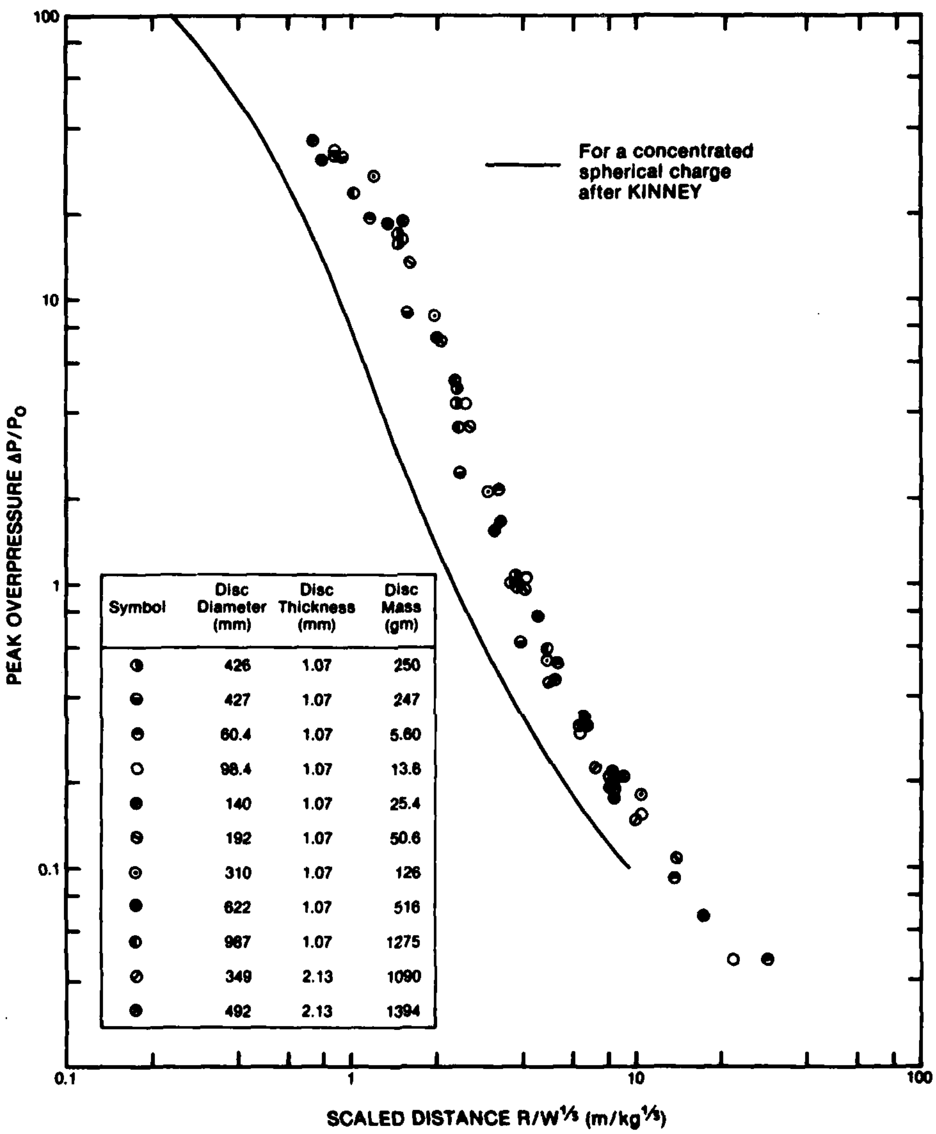

Fig. 11 - Air-blast decay from detonation of Detasheet initiator discs with diameters ranging from 60.4 mm to 987 mm. Peak normalized overpressure $\Delta P/P_0$ measured at different distances R (in meters) from the charge along the central axis perpendicular to the plane of the disc is shown as a function of $R/W^{1/3}$ where W is the total mass of explosive charge in kg. The solid curve is the blast decay from a concentrated TNT charge.[21]

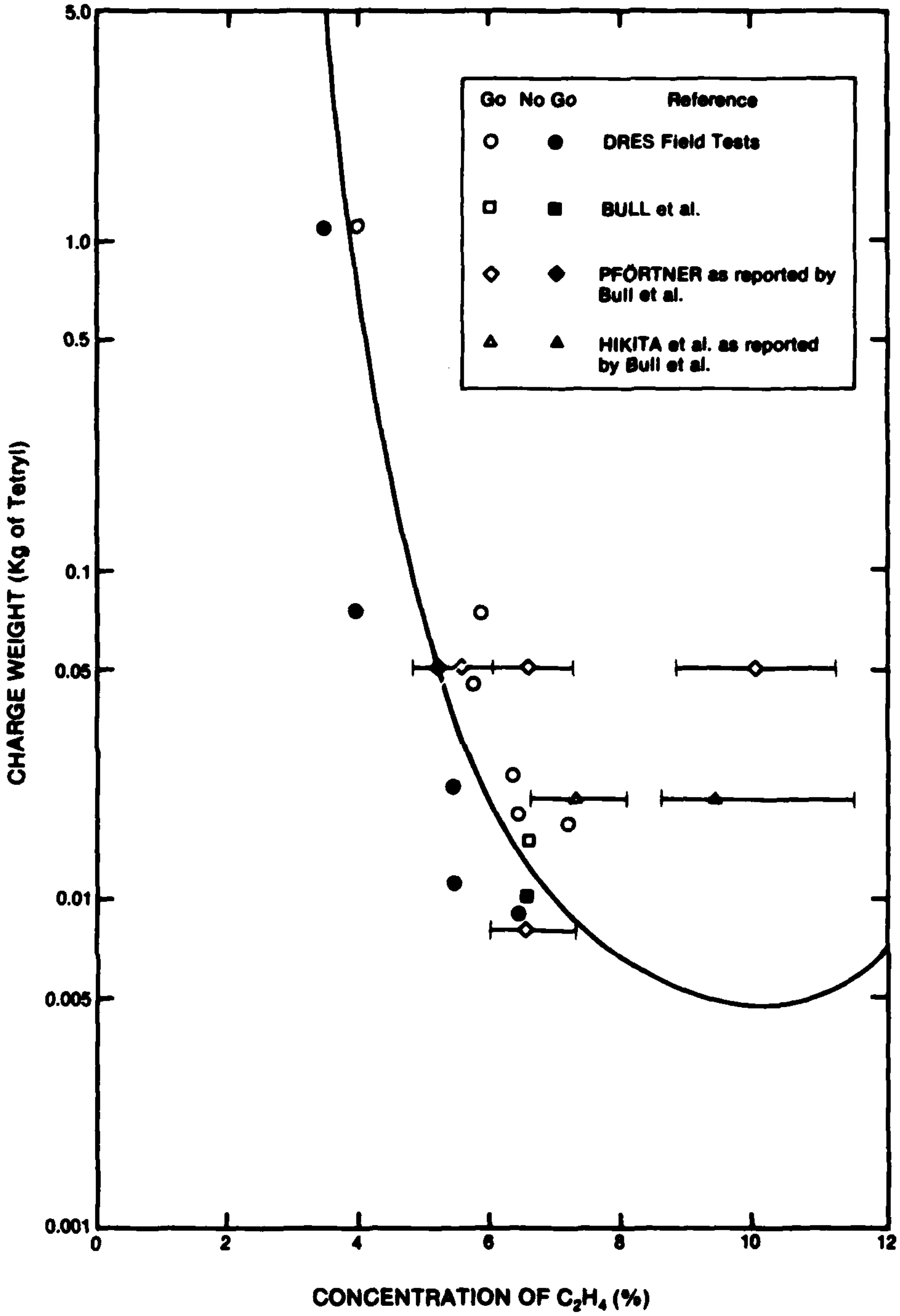

Fig. 12 – Solid explosive initiator charge weight (kg of tetryl) vs. % C_2H_4 in C_2H_4-air mixtures. Bull et al. — Ref. 5,6; Hikita — Ref. 22.

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The results of a series of field tests performed to determine the critical energy required for initiation of detonation in ethylene-air mixtures are described and discussed, with particular emphasis on the influence of the bag size on the initiation and propagation of detonation. The tests were performed in a plastic bag 10 m long with a cross-sectional area of 1.83 m x 1.83 m using discs of Detasheet explosive as initiator charges at one end of the bag.

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